Searching for dark matter with liquid-argon detectors

Marek Walczak

The Global Argon Dark Matter Collaboration

High Energy Physics Seminar, 24 Mar. 2023

European Funds
Smart Growth

Republic of Poland

FNP Foundation for Polish Science

European Union
European Regional Development Fund

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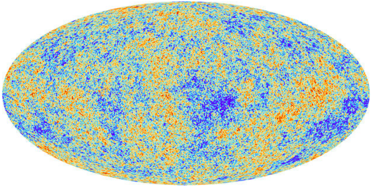
evidence for dark matter



evidences:

- anisotropies in the cosmic microwave background radiation
- gravitational lensing
- rotation curves of disc galaxies
- large scale structures

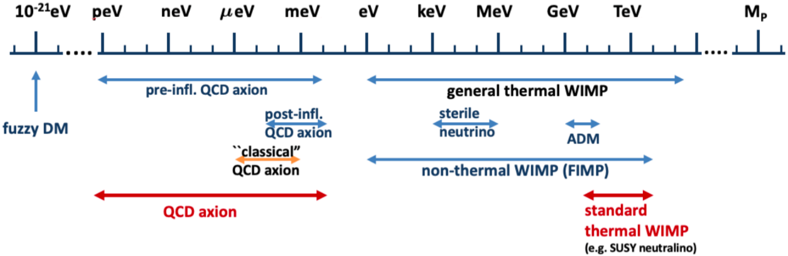
searches:

- colliders
- indirect (from dark matter anihilation)
- direct (by interaction with target mass: temp. increase, sound wave, ionzation)

dark matter candidates

general properties:

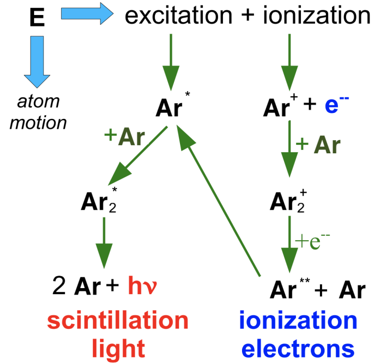
cold, non-baryonic, does not dissipate its energy, stable (or extremely long lived)



APPEC Committee Report, arXiv:2104.07634

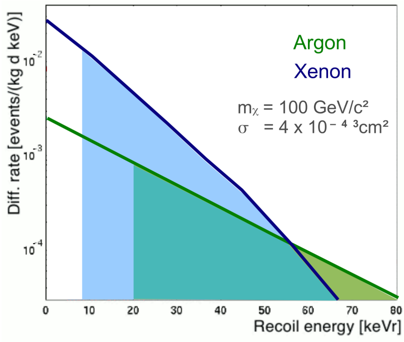
interactions in liquid noble gas

arXiv:1206.2169



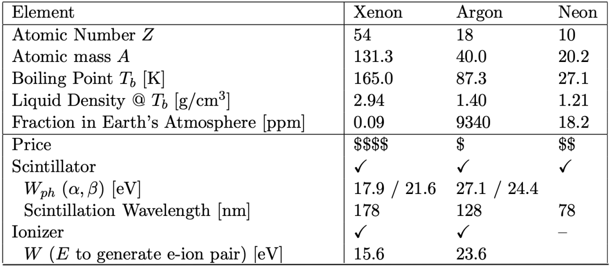
excitation and ionization of the target (Xe works the same)

expected nuclear recoil spectra



experimentally achieved thresholds indicated by the colored areas

liquid noble gas as target mass

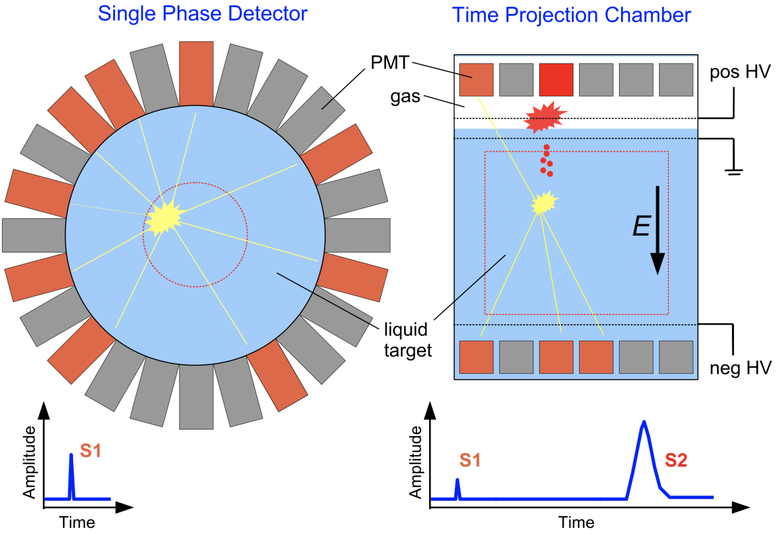


Element	Xenon	Argon	Neon
Atomic Number Z	54	18	10
Atomic mass A	131.3	40.0	20.2
Boiling Point T_b [K]	165.0	87.3	27.1
Liquid Density @ T_b [g/cm^3]	2.94	1.40	1.21
Fraction in Earth's Atmosphere [ppm]	0.09	9340	18.2
Price	\$\$\$\$	\$	\$\$
Scintillator	✓	✓	✓
W_{ph} (α, β) [eV]	17.9 / 21.6	27.1 / 24.4	
Scintillation Wavelength [nm]	178	128	78
Ionizer	✓	✓	–
W (E to generate e-ion pair) [eV]	15.6	23.6	

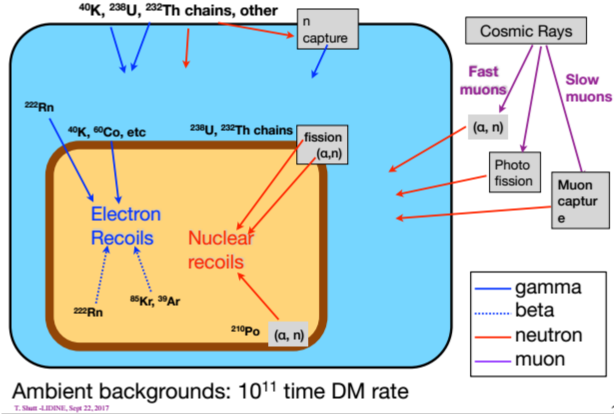
Argon:

- dense and easy to purify, scalable,
- high ionization, good scintillator, transparent to own scintillation,
- strong electron recoil discrimination via pulse shape,
- scintillation light peaks at 128 nm, a wavelength shifter (WLS) is required for its detection

liquid noble gas detector concepts



backgrounds



Ambient backgrounds: 10^{11} time DM rate

T. Shutt -LIDINE, Sept 22, 2017

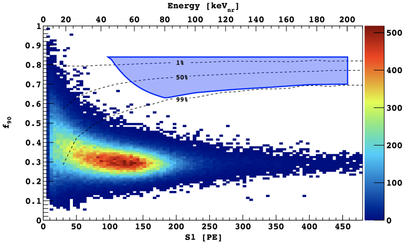
cosmic radiation -> go underground

natural radioactivity -> shielding

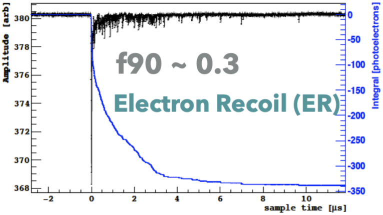
detector material radioactivity -> radiopurity, fiducialisation

pulse shape discrimination in Ar

Results from a run of DarkSide-50 with a UAr fill for a 532.4 live-days livetime:

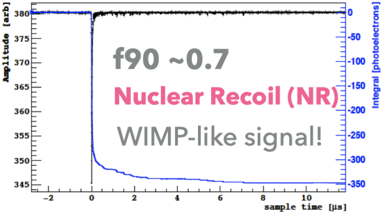


- $\mathbf{f_{90}}$: fraction of the primary scintillation pulse in its first 90 ns
- **S1**: total integral of the primary scintillation pulse (photoelectrons, PE)
- **PSD**: tool to distinguish light from a recoiling electron and nuclear recoil
  - for PSD capabilities for DEAP-3600 detector see also [Eur. Phys. J. C 81, 823 (2021)]



f90 ~ 0.3

Electron Recoil (ER)



f90 ~0.7

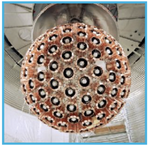
Nuclear Recoil (NR)

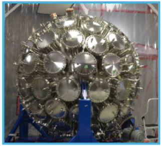
WIMP-like signal!

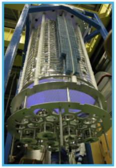
The Global Argon Dark Matter Collaboration

The Global Argon Dark Matter Collaboration - 500 people


DarkSide-50


DEAP-3600


MiniCLEAN

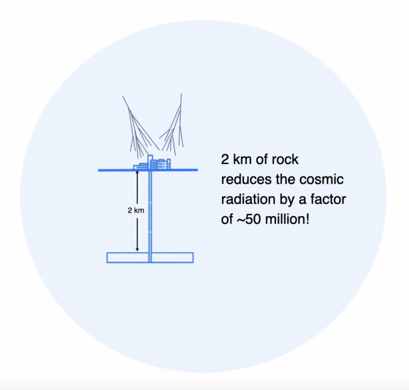

ArDM

Goal: continue work on DS-50 and DEAP-3600,
build: DarkSide-20k, DarkSide-LowMass and in future ARGO

DarkSide-20k Technical Design Report submitted to INFN in Dec 2021

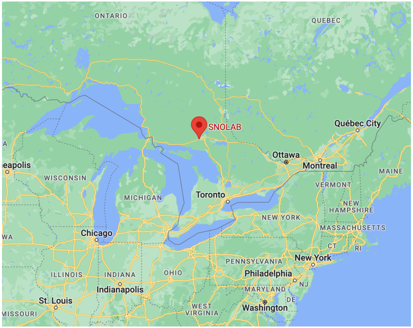
The Global Argon Dark Matter Collaboration

SNOLAB



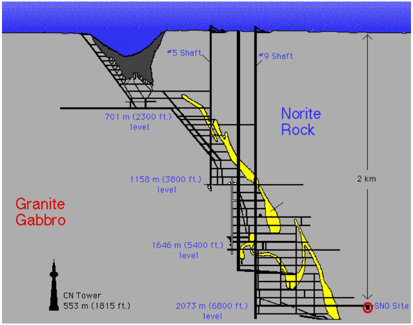
2 km of rock reduces the cosmic radiation by a factor of ~50 million!

- Canadian underground science laboratory
- formed in 1984 with the goal of solving the solar neutrino problem



- Vale's Creighton nickel mine near Sudbury, Ontario

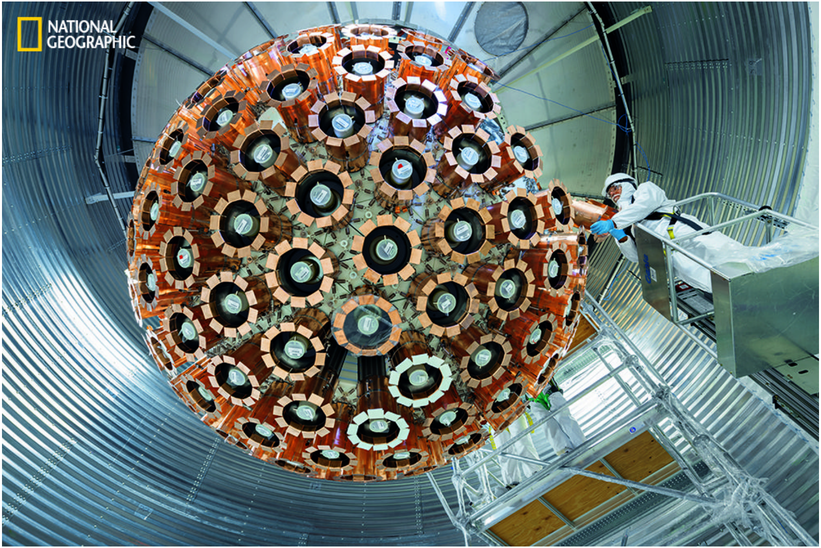
SNOLAB



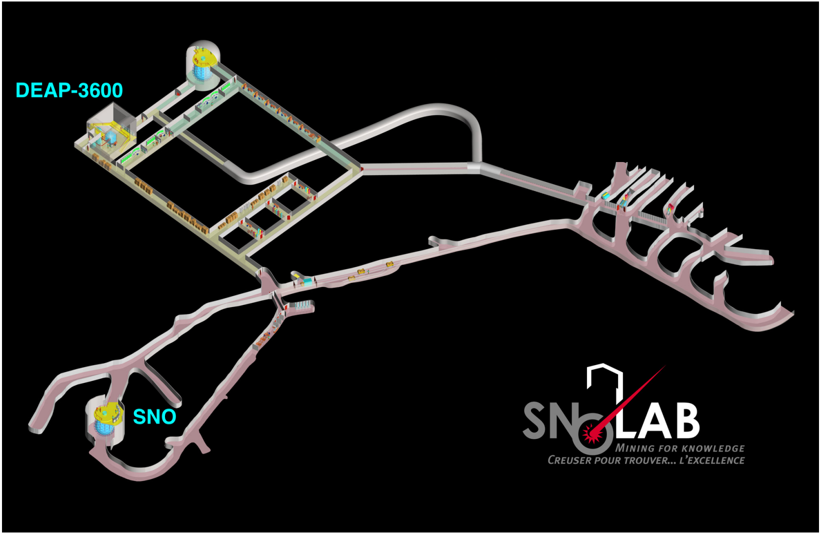
- deepest cleanest lab in the world (class-2000 cleanroom)

- low-background environment
- experiments requiring extremely high sensitivities

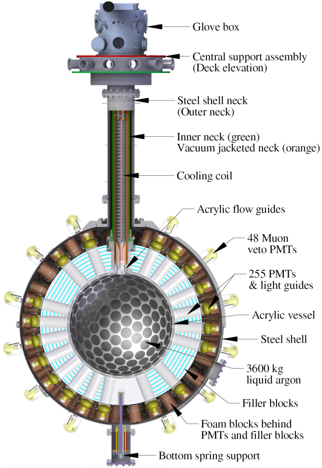
DEAP-3600



DEAP-3600

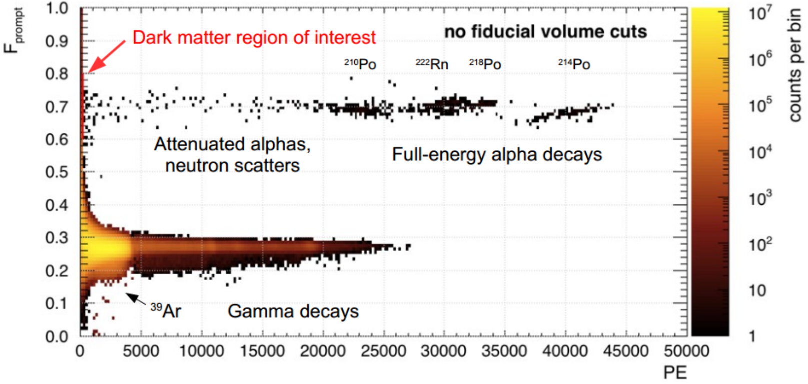

DEAP-3600
SNO
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

DEAP-3600



- 3.3 tonne liquid argon target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel
- vacuum evaporated TPB WLS (10 m^2 surface)
- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- immersed in 8 m water shield, instrumented with PMTs to veto muons

DEAP-3600 results

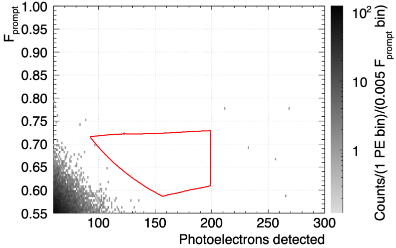


First DEAP-3600 dark matter search, with 4.4 live days

Phys. Rev. Lett. 121, 071801 (2018) arXiv:1707.08042

DEAP-3600 results

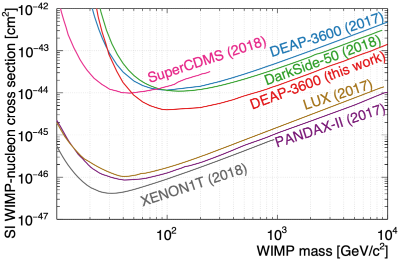
231 live-days dataset (Nov ‘16 – Oct ‘17)



Observed F_{prompt} vs. PE distribution after all cuts. The region of interest is shown in red.

1) < 0.05 electron recoils backgrounds
2) 1% nuclear recoils acceptance loss
3) < 0.5 neck a backgrounds
4) more a and neutron backgrounds, few WIMP events expected

Phy. Rev. D, 100, 022004 (2019)



90% confidence upper limit on the spin- independent WIMP-nucleon cross sections

DEAP-3600

about 100 scientists from Canada, UK, Mexico, Germany, US, Italy, Spain, Russia and Poland

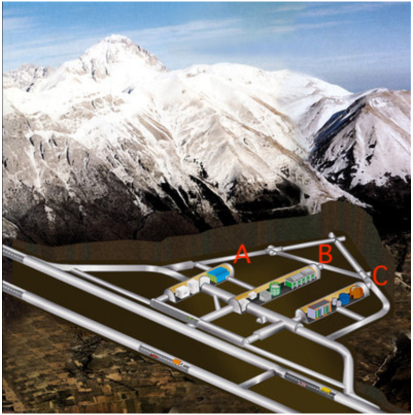
2022 DEAP-3600 Collaboration meeting in Canada

Laboratori Nazionali del Gran Sasso (LNGS)

- founded in 1987
- largest underground research center
- covered by 1400 m of rock (3800 mwe shielding)
- can be accessed by car

- Abruzzo region in central Italy, 120 km from Rome
- below Gran Sasso mountain in Italy

Laboratori Nazionali del Gran Sasso (LNGS)



- **DarkSide-50**: hosted in Hall-C

- collected data since 2013 till 2019

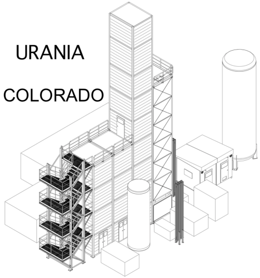
- **DarkSide-20k** will be installed in LNGS in Hall-C

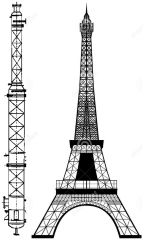
- construction: 2022 - 2025

- nominal duration of operation: 10 years

Hall-C in LNGS

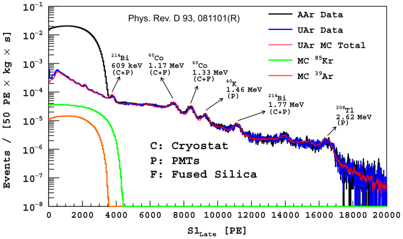
DarkSide: Underground Argon





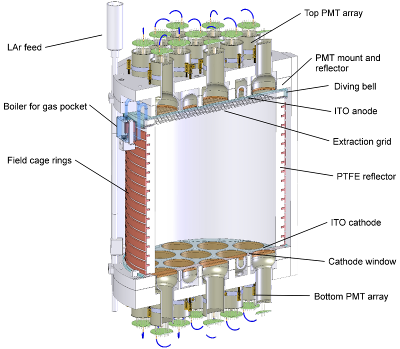
ARIA, Seruci mine in Sardinia

- URANIA: Colorado, capacity of 330 kg/day of Underground Ar
- ARIA: 350 m tall column - removes the remaining nitrogen from UAr. Assembly of the column in the shaft this year [Eur. Phys. J. C 81, 359 (2021)]

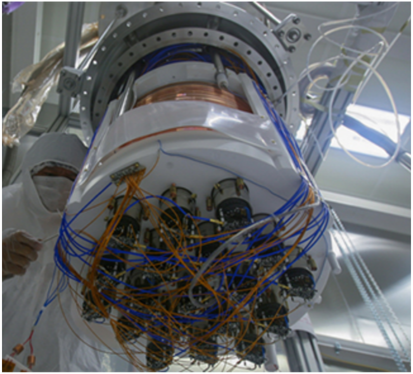


- **^{39}Ar reduction factor of at least 1400**(to be measured by DArT [JINST 15, P02024 (2020)])

DarkSide-50



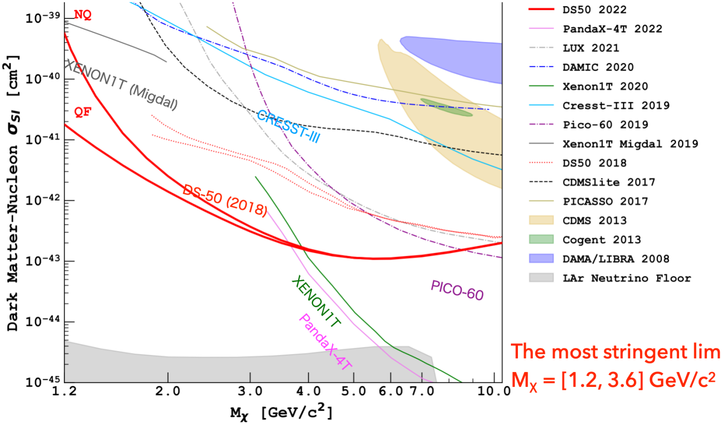
- two-phase argon TPC
- cylindrical volume with UAr
- 2 x 19 3 inch Hamamatsu R11065 PMTs
- windows coated with Indium-Tin-Oxide
- 1 cm-thick gas pocket under the anode



- grid 4.7mm beneath GAr separates drift and extraction regions
- surfaces coated with TetraPhenylButadiene (TPB)
- liquid-scintillator neutron and γ veto
- water Cherenkov veto: shielding and muons

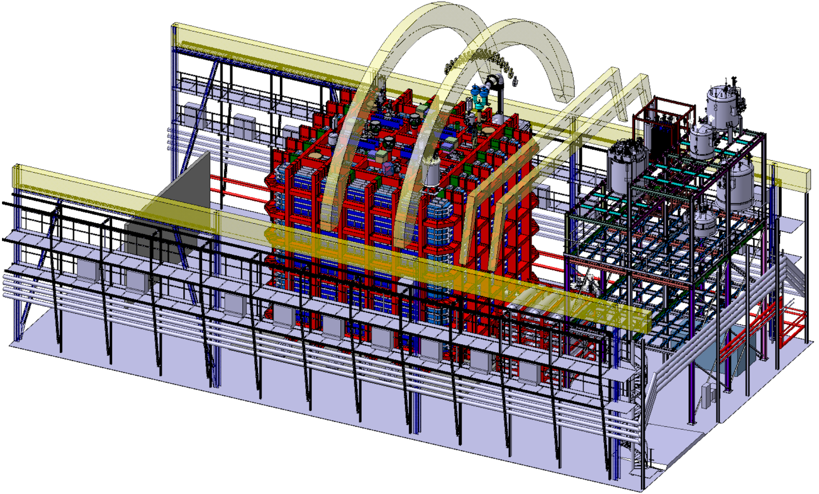
DarkSide-50

arXiv:2207.11966

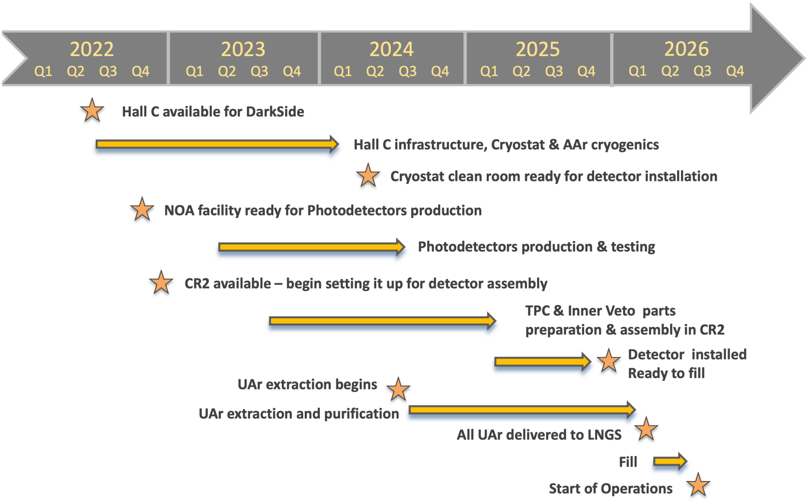


The most stringent limit at M_χ = [1.2, 3.6] GeV/c^2

DarkSide-20k



DarkSide-20k schedule


2022 Q1 Q2 Q3 Q4
2023 Q1 Q2 Q3 Q4
2024 Q1 Q2 Q3 Q4
2025 Q1 Q2 Q3 Q4
2026 Q1 Q2 Q3 Q4

Hall C available for DarkSide

Hall C infrastructure, Cryostat & AAr cryogenics

Cryostat clean room ready for detector installation

NOA facility ready for Photodetectors production

Photodetectors production & testing

CR2 available – begin setting it up for detector assembly

TPC & Inner Veto parts
preparation & assembly in CR2

Detector installed
Ready to fill

UAr extraction begins

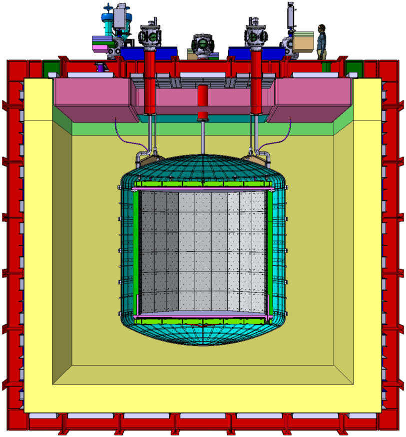
UAr extraction and purification

All UAr delivered to LNGS

Fill

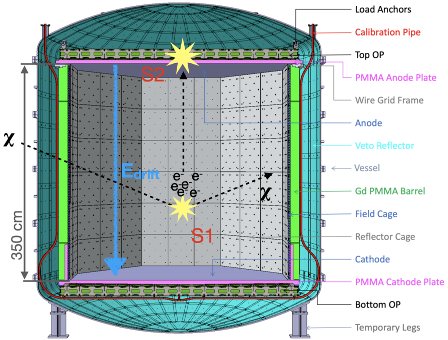
Start of Operations

DarkSide-20k overview



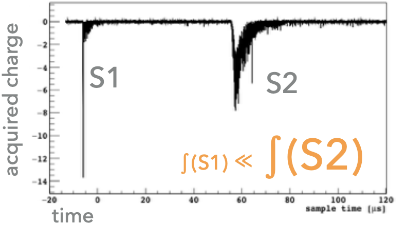
- Time Projection Chamber (TPC) filled with 51 t of underground Ar (UAr) (20 t fiducial)
- Acrylic panels loaded with gadolinium (Gd-PMMA)
- Neutron veto buffer between the TPC and the vessel
- Vessel contains UAr
- Outer cosmic veto filled with atmospheric Ar (AAr) - muons and their shower products
- WLS: TPB coating in TPC, PolyEthylene Naphthalate (PEN) foils in the veto

Dual Phase Time Projection Chamber

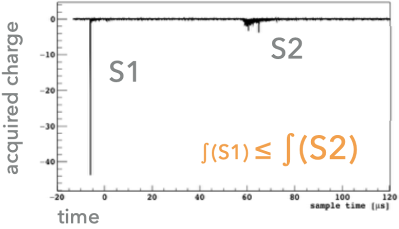


- S1: energy and pulse shape discrimination (PSD)
- S2: energy information and the 3D position measurement of the event
- Resolution: 10 mm horizontal,1 mm vertical

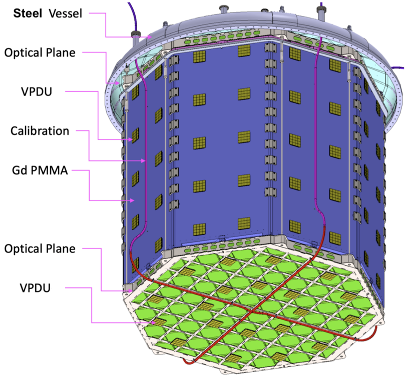
Electron Recoil (ER)



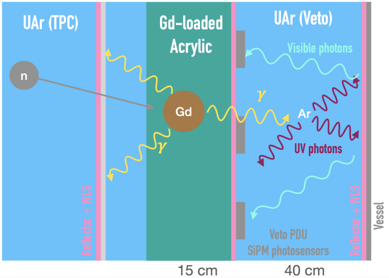
Nuclear Recoil (NR)



Neutron Veto



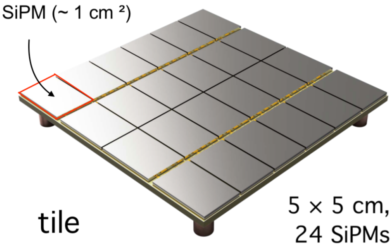
Neutrons elastically scattering from argon nuclei are indistinguishable from WIMPs.

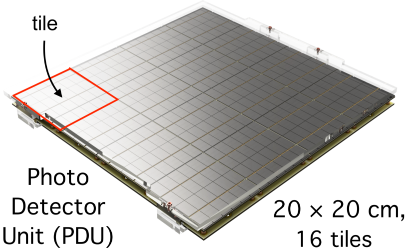


- 40 cm thick space between the vessel and Gd-PMMA
- 8 walls made from 15 cm thick Gd-PMMA
- ESR reflector with PEN WLS foils on all the surfaces

- Neutrons are moderated in the PMMA and captured by Gd,
- Gd emits multiple γs with energy up to 8 MeV,
- UAr scintillation light is shifted and detected by veto photodetectors

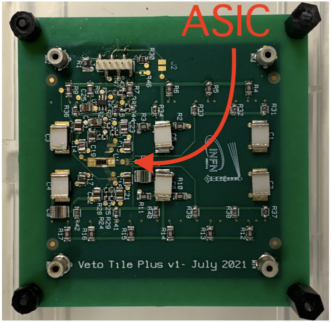
Silicon photomultipliers





- Custom silicon photomultipliers (SiPM)
- low noise at 88K, tuned sensitivity vs light spectrum
- Photon detection efficiency: 45%
- Timing resolution: 10 ns
- Dark-count rate: few mHz/mm^2
- 26 m^2 overall
- 156 PDUs for the veto (vPDUs)
- Enhanced Specular Reflector (ESR) film covers all passive surfaces

Veto tile tests - Genova 2021



- ASIC - application specific integrated circuit - coupled to SiPM
- Customized for a particular use
- Linear behavior up to 700 mV and an RMS noise of 0.8 mV

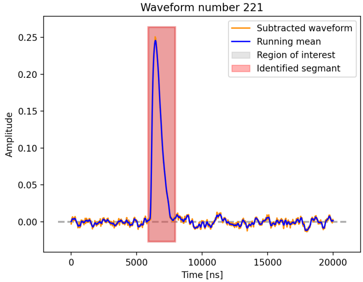
Tests performed in Genova

Tests at warm and cold (liquid nitrogen) included:

- current draw,
- RMS and baseline,
- SNR vs VoV,
- thermal cycle, stability

Veto tile tests in Genova

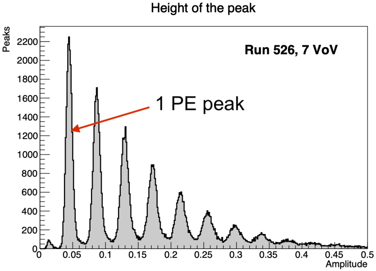
Waveform with laser pulse after the reconstruction with the DarkSide reconstruction software



sampling rate: 250 MHz

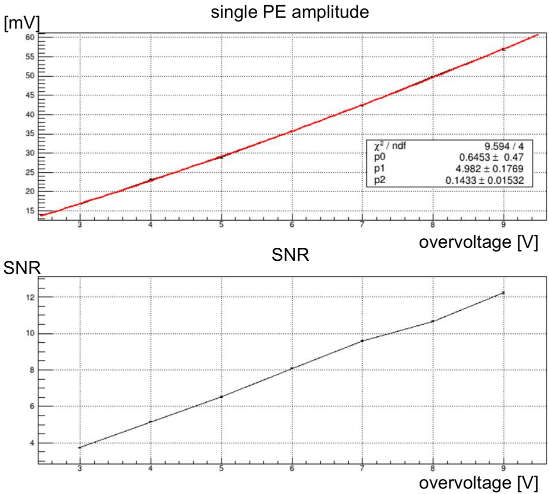
running mean gate: 120 ns

Multi photoelectron (PE) plot (finger plot) for the veto tile obtained during tests at cold in Genova



Bump on the left comes from the noise and depends on the threshold for finding peaks (8 RMS here).

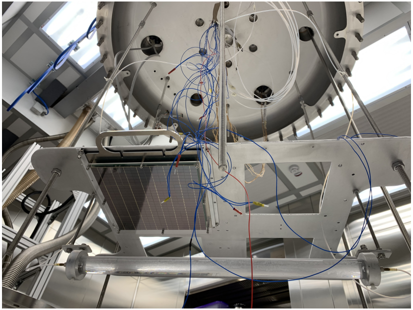
Veto tile tests in Genova



vTile connected to 1/4 Mother Board – @ 7 VoV:

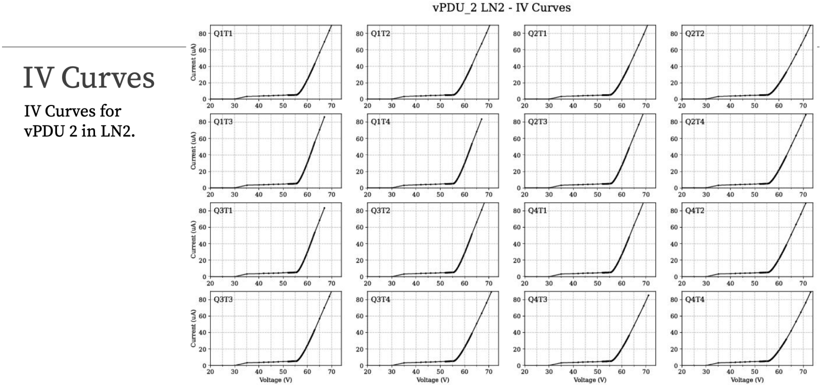
1 PE amplitude = 42 mV, RMS = 4.5 mV, SNR = 9.5

veto PDU tests in INFN Napoli - March 2023



- tests at warm and cold
- finger plots with laser
- stability tests over 5 days

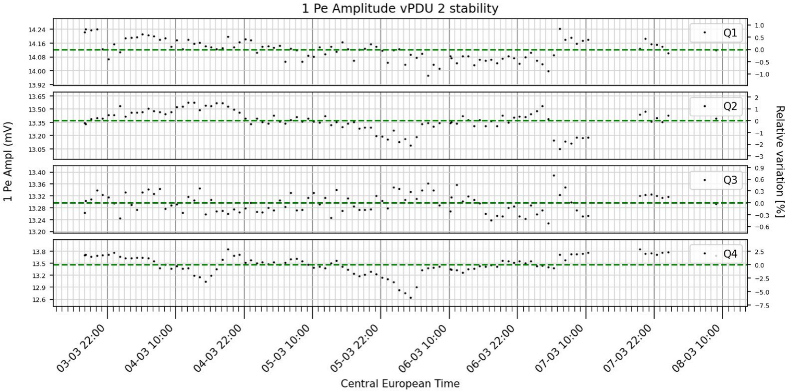
veto PDU tests in INFN Napoli - March 2023


IV Curves

IV Curves for vPDU 2 in LN2.

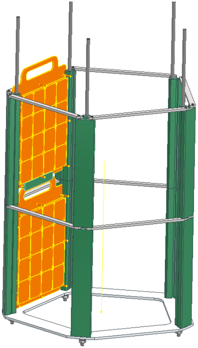
veto PDU tests in INFN Napoli - March 2023

Stability (5 days): vPDU 2, Amplitude of 1 PE



Cryogenic veto PDU tests

- Tests of the final veto PDUs will start this year
- AstroCeNT (Warsaw), Edinburgh and Liverpool
- Cryogenic tests in liquid Nitrogen

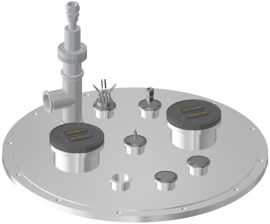


Setup in AstroCeNT: 10 PDUs per 1 week cycle

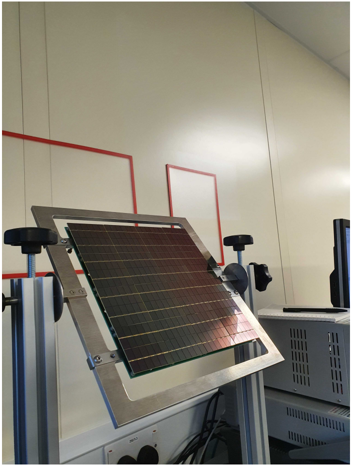
AstroCeNT setup in CEZAMAT (Warsaw): Commercial dewar, 50 cm diameter, 130 cm height
Midas DAQ, CAEN digitizers and electronics

veto PDU tests

custom made cover:

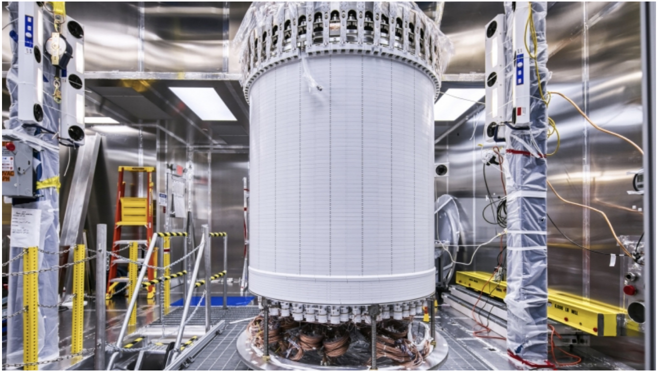


Tests will include: current draw, SNR vs Vov, RMS and baseline, dark count rate, cross talk, after-pulse, thermal cycle resistance, stability tests



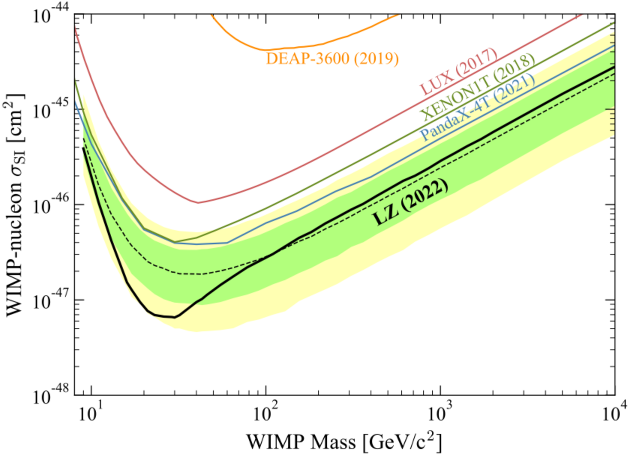
veto PDU just arrived from Naples to Warsaw for tests and our system setup

LUX-ZEPLIN (LZ) Experiment



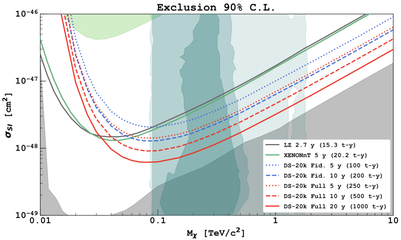
10 tons of liquid xenon, Dual Phase TPC

LZ leading result



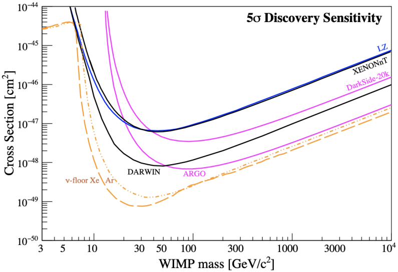
arXiv:2207.03764v3

sensitivity to spin independent WIMPs



90% C.L. exclusion limits for DarkSide-20K for different lengths of runs compared to the currently funded experiments: LZ and XENONnT that are expected to lead the field for high mass WIMPs searches in the next few years

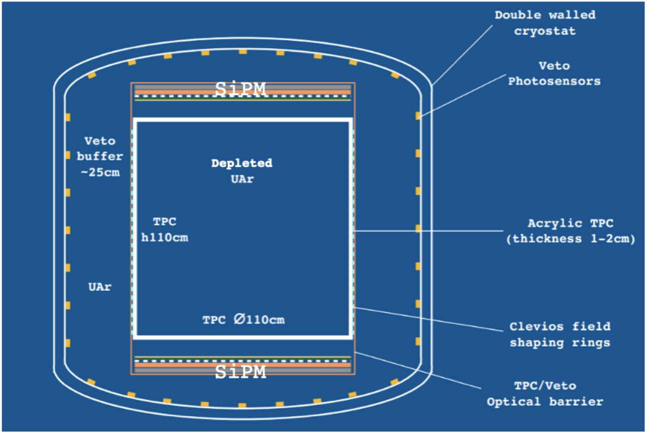
Direct Detection of Dark Matter – APPEC Committee Report, arXiv:2104.07634



Projected 5σ discovery sensitivity of upcoming and proposed experiments:

- XENONnT (LXe, 20 t-y),
- LZ (LXe, 15,3 t-y),
- DarkSide-20k (LAr, 200 t-y),
- DARWIN (LXe, 200 t-y),
- ARGO (LAr, 3000 t-y).

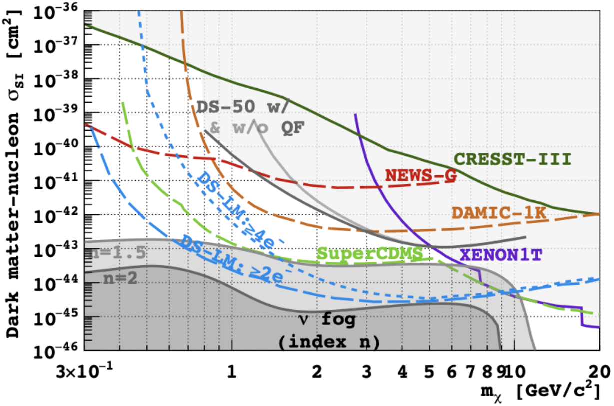
DarkSide-LowMass



1 T of UAr: low activity of ^{39}Ar, low impurity

ultra-pure photo-sensor and cryostat

DarkSide-LowMass



https://arxiv.org/abs/2209.01177

other scenarios: inealstic boosted DM search

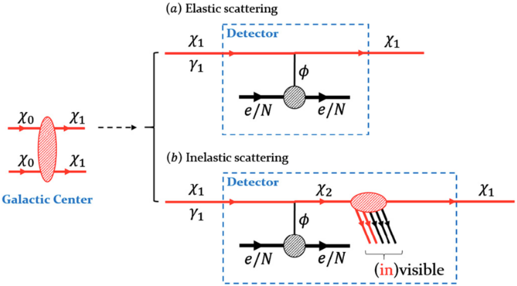
Physics Letters B 780 (2018) 543–552

Inelastic Boosted Dark Matter at direct detection experiments

Gian F. Giudice [a,*], Doojin Kim [a,*], Jong-Chul Park [b,*], Seodong Shin [c,d,*]

[a] *Theoretical Physics Department, CERN, Geneva, Switzerland*
[b] *Department of Physics, Chungnam National University, Daejeon 34134, Republic of Korea*
[c] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[d] *Department of Physics & IPAP, Yonsei University, Seoul 03722, Republic of Korea*

iBDM model



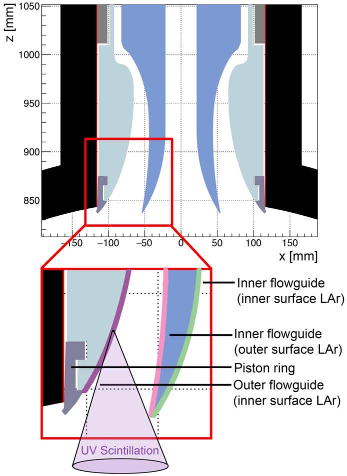
The ordinary boosted DM (upper part) and iBDM (lower part) scenarios with the relevant DM-signal processes under consideration.

- $\boldsymbol{\chi_0}$: heavy, cold, no direct coupling to SM particles but pairannihilates into two χ_1's
- $\boldsymbol{\chi_1}$: light, boosted, interacts with SM particles
- $\boldsymbol{\chi_2}$: heavier (than χ_1), unstable dark sector particle
- communication with dark sector through mixing (ε coefficient) with dark photon **X**

Conclusions

- DEAP-3600
    - Stable data collection for DM search, world leading PSD
    - 802 live days (Nov 2016 – March 2020, 80% blind since Jan 2018)
    - upgrade, new DM searches and physics analyses
- DarkSide program
    - UAr: ^{39}Ar reduction factor of at least 1400
    - background-free Dark Matter search thanks to strong PSD, radio pure materials and novel neutron veto
    - DarkSide-50 leading limit for low mass WIMP
    - construction of the DarkSide-20k cryostat starts now, data taking in 2026
    - DarkSide-LowMass: would go down to the neutrino fog for 1 – 10 GeV WIMPs
- Argon: excellent properties suited to high and low mass WIMP searches

DEAP-3600 backgrounds



	Source	N^{CR}	$N^{\mathrm{ROI,\ LL}}$	N^{ROI}
β/γ's	ERs	2.44×10^9	0.34 ± 0.11	0.03 ± 0.01
	Cherenkov	$< 3.3 \times 10^5$	< 3890	< 0.14
n's	Radiogenic	6 ± 4	11^{+8}_{-9}	$0.10^{+0.10}_{-0.09}$
	Cosmogenic	<0.2	<0.2	<0.11
α's	AV surface	<3600	< 3000	< 0.08
	AV Neck FG	28^{+13}_{-10}	28^{+13}_{-10}	$0.49^{+0.27}_{-0.26}$
	Total	N/A	< 4910	$0.62^{+0.31}_{-0.28}$

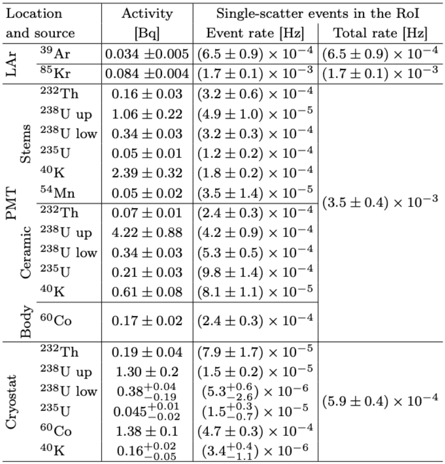
Predicted number of events from each background source

For each background component a control region (CR) is defined by an event selection in the physics data.

AV - acrylic vessel

FG - acrylic flowguides

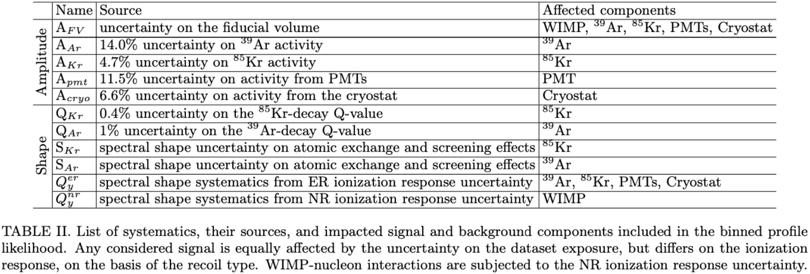
DS-50 backgrounds



Location and source			Activity [Bq]	Single-scatter events in the RoI	
				Event rate [Hz]	Total rate [Hz]
LAr		^{39}Ar	0.034 ±0.005	$(6.5 \pm 0.9) \times 10^{-4}$	$(6.5 \pm 0.9) \times 10^{-4}$
		^{85}Kr	0.084 ±0.004	$(1.7 \pm 0.1) \times 10^{-3}$	$(1.7 \pm 0.1) \times 10^{-3}$
PMT	Stems	^{232}Th	0.16 ± 0.03	$(3.2 \pm 0.6) \times 10^{-4}$	$(3.5 \pm 0.4) \times 10^{-3}$
		^{238}U up	1.06 ± 0.22	$(4.9 \pm 1.0) \times 10^{-5}$	
		^{238}U low	0.34 ± 0.03	$(3.2 \pm 0.3) \times 10^{-4}$	
		^{235}U	0.05 ± 0.01	$(1.2 \pm 0.2) \times 10^{-4}$	
		^{40}K	2.39 ± 0.32	$(1.8 \pm 0.2) \times 10^{-4}$	
		^{54}Mn	0.05 ± 0.02	$(3.5 \pm 1.4) \times 10^{-5}$	
	Ceramic	^{232}Th	0.07 ± 0.01	$(2.4 \pm 0.3) \times 10^{-4}$	
		^{238}U up	4.22 ± 0.88	$(4.2 \pm 0.9) \times 10^{-4}$	
		^{238}U low	0.34 ± 0.03	$(5.3 \pm 0.5) \times 10^{-4}$	
		^{235}U	0.21 ± 0.03	$(9.8 \pm 1.4) \times 10^{-4}$	
		^{40}K	0.61 ± 0.08	$(8.1 \pm 1.1) \times 10^{-5}$	
	Body	^{60}Co	0.17 ± 0.02	$(2.4 \pm 0.3) \times 10^{-4}$	
Cryostat		^{232}Th	0.19 ± 0.04	$(7.9 \pm 1.7) \times 10^{-5}$	$(5.9 \pm 0.4) \times 10^{-4}$
		^{238}U up	1.30 ± 0.2	$(1.5 \pm 0.2) \times 10^{-5}$	
		^{238}U low	$0.38^{+0.04}_{-0.19}$	$(5.3^{+0.6}_{-2.6}) \times 10^{-6}$	
		^{235}U	$0.045^{+0.01}_{-0.02}$	$(1.5^{+0.3}_{-0.7}) \times 10^{-5}$	
		^{60}Co	1.38 ± 0.1	$(4.7 \pm 0.3) \times 10^{-4}$	
		^{40}K	$0.16^{+0.02}_{-0.05}$	$(3.4^{+0.4}_{-1.1}) \times 10^{-6}$	

TABLE I. Background activities and event rate in the RoI from the bulk, PMTs, and cryostat from material screening.

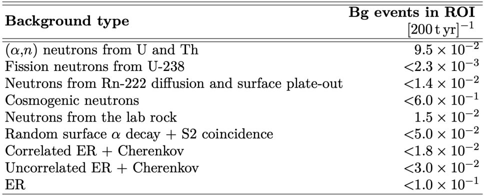
DS-50 syst



	Name	Source	Affected components
Amplitude	A_{FV}	uncertainty on the fiducial volume	WIMP, ^{39}Ar, ^{85}Kr, PMTs, Cryostat
	A_{Ar}	14.0% uncertainty on ^{39}Ar activity	^{39}Ar
	A_{Kr}	4.7% uncertainty on ^{85}Kr activity	^{85}Kr
	A_{pmt}	11.5% uncertainty on activity from PMTs	PMT
	A_{cryo}	6.6% uncertainty on activity from the cryostat	Cryostat
Shape	Q_{Kr}	0.4% uncertainty on the ^{85}Kr-decay Q-value	^{85}Kr
	Q_{Ar}	1% uncertainty on the ^{39}Ar-decay Q-value	^{39}Ar
	S_{Kr}	spectral shape uncertainty on atomic exchange and screening effects	^{85}Kr
	S_{Ar}	spectral shape uncertainty on atomic exchange and screening effects	^{39}Ar
	Q_y^{er}	spectral shape systematics from ER ionization response uncertainty	^{39}Ar, ^{85}Kr, PMTs, Cryostat
	Q_y^{nr}	spectral shape systematics from NR ionization response uncertainty	WIMP

TABLE II. List of systematics, their sources, and impacted signal and background components included in the binned profile likelihood. Any considered signal is equally affected by the uncertainty on the dataset exposure, but differs on the ionization response, on the basis of the recoil type. WIMP-nucleon interactions are subjected to the NR ionization response uncertainty.

DS-20k backgrounds



Background type	**Bg events in ROI** $[200\,\mathrm{t\,yr}]^{-1}$
(α,n) neutrons from U and Th	9.5×10^{-2}
Fission neutrons from U-238	$<2.3 \times 10^{-3}$
Neutrons from Rn-222 diffusion and surface plate-out	$<1.4 \times 10^{-2}$
Cosmogenic neutrons	$<6.0 \times 10^{-1}$
Neutrons from the lab rock	1.5×10^{-2}
Random surface α decay + S2 coincidence	$<5.0 \times 10^{-2}$
Correlated ER + Cherenkov	$<1.8 \times 10^{-2}$
Uncorrelated ER + Cherenkov	$<3.0 \times 10^{-2}$
ER	$<1.0 \times 10^{-1}$

Nuclear recoil (NR) backgrounds expected during the full DS-20k exposure, based on current data and Monte Carlo simulations.